

PeV neutrinos from intergalactic interactions of cosmic rays emitted by active galactic nuclei

Oleg E. Kalashev,¹ Alexander Kusenko,^{2,3} and Warren Essey²

¹*Institute for Nuclear Research, 60th October Anniversary Prospect 7a, Moscow 117312 Russia*

²*Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547, USA*

³*IPMU, University of Tokyo, Kashiwa, Chiba 277-8568, Japan*

The observed spectra of distant blazars are well described by secondary gamma rays produced in line-of-sight interactions of cosmic rays with background photons. In the absence of the cosmic-ray contribution, these spectra would appear surprisingly hard, but the cosmic ray interactions generate very high energy gamma rays relatively close to the observer, and the spectra agree with the data. The same interactions of cosmic rays are expected to produce a flux of neutrinos with energies peaked around 1 PeV. We show that the predicted diffuse isotropic neutrino background from many distant sources can explain the neutrino events recently detected by the IceCube experiment. We also find that the flux from any individual nearby source is insufficient to account for these events. The narrow spectrum around 1 PeV implies that a typical active galactic nucleus can accelerate protons to EeV energies.

PACS numbers: 95.85.Ry, 98.70.Sa, 98.54.-h, 98.54.Cm

The IceCube collaboration has detected two neutrinos with energies 1.1 PeV and 1.3 PeV (35% systematic error) [1]. These neutrinos are either electron or tau neutrinos. The muon analysis, currently under way, is expected to produce additional events (probably, with a lower energy resolution). The narrow energy range in which the two neutrinos have been detected indicates that the source has a peak somewhere around a PeV energy, above the experimental threshold of 0.4 PeV and below the Glashow resonance that enhances detector sensitivity around 6.8 PeV [2]. While a number of astrophysical processes can be responsible for high-energy neutrinos, only specific types of sources can produce a peaked spectrum around a PeV [3].

Narrow spectra peaked around 1 PeV were predicted to arise from line-of-sight interactions of cosmic rays emitted by blazars [4] if the spectrum of protons terminates at $E_{p,\max} \lesssim 10^9$ GeV [4]. There is growing evidence that intergalactic cascades initiated by line-of-sight interactions of cosmic rays produced by active galactic nuclei (AGNs) are responsible for the highest-energy gamma rays observed from blazars [4–12]. Blazar spectra are explained remarkably well with secondary photons from such cascades [4–6], while, in the absence of such contribution, some unusually hard intrinsic spectra [13–15] or hypothetical new particles [16] have been invoked to explain the data. Models for hard intrinsic spectra of γ rays can be constructed, but the natural ease with which secondary photons reproduce the data makes the explanation based on cosmic rays very appealing. Furthermore, detailed theoretical models show that relativistic shocks can effectively accelerate cosmic rays to energies $\sim 10^8$ GeV, but higher energies may require rather exceptional conditions [17]. Secondary gamma rays explain the blazar spectra as long as the magnetic fields are in the femtogauss range [18].

The mechanism predicts that some neutrinos with a peaked spectrum should be produced in interactions of protons with extragalactic background light (EBL) [4, 5]. We will examine whether these neutrinos can account for PeV neutrino events in IceCube.

Assuming the scenario of Refs. [4–12], we have considered two possibilities for the origin of IceCube neutrinos: a single nearby source, and a combined contribution of distant sources. Two important constraints have to be satisfied: the gamma-ray background and the cosmic-ray spectrum should not exceed the observed fluxes. We do not assume that the cosmic ray spectrum up to ultrahigh energies is explained by the same sources; as was pointed out in Ref. [19], such a scenario disagrees with the data. Furthermore, we do not consider neutrinos produced inside cosmic-ray sources as in Ref. [20].

The total neutrino flux (summed over flavors) is uncertain, and the numerical value depends on the shape of the spectrum. For crude estimates, one can use

$$E_\nu^2 \frac{dF}{dE_\nu} \simeq 20 \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (1)$$

where E_ν is the neutrino energy. However, this numerical value can be misleading. In comparing our model with the IceCube data, we do not rely on this number, but we calculate the expected number of events using the spectral shape predicted by our model, as described below.

For the case of one or a few nearby point sources, we have not been able to find an acceptable explanation of the IceCube events. Indeed, the neutrino required flux is an order of magnitude greater than the predicted flux from a single source shown in Ref. [4]. A single source at a smaller distance from Earth than the blazars considered in Ref. [4] would produce an unacceptably large flux of cosmic rays. A careful numerical analysis confirms

this conclusion. We, therefore, proceed to considering the second possibility: a diffuse background from distant sources.

For the diffuse flux calculation we use the numerical code described in detail in Ref. [21]. The code is based on kinetic equations; it calculates the propagation of nucleons, stable leptons and photons using the standard dominant processes, *i.e.* pion production by nucleons, e^\pm pair production by protons and neutron β -decays. For electron-photon cascade development, it includes e^\pm pair production and inverse Compton scattering. We also take into account neutrino oscillations on their way from the site of production to the observer. Since the distance traveled by neutrinos is much greater than the oscillation length, muon neutrinos oscillate into tau neutrinos with a 50% probability. The resulting spectrum has a flavor ratio of approximately (1:1:1). We note that in our numerical calculations we use the actual mixing angles in the tri-bimaximal neutrino mixing approximation.

A number of different models have been advanced for EBL [22–24]. There are some upper bounds on EBL in the literature that were based on observations of distant blazars but were derived without taking into account the cosmic ray contribution. When the cosmic rays are included, these bounds on EBL are relaxed [6]. We, therefore, consider a broad range of models. Since most the neutrinos are produced near the threshold, only the height of the EBL peak near $1\mu\text{m}$ affects the results. At those wavelengths, the model of Ref. [22] predicts a higher photon density than most other models. At the lower side of the range for $1\mu\text{m}$ EBL density are the models of Ref. [23] and Ref. [25]. We show the spectra for these three models in Fig. 1.

While AGNs are widely expected to be able to accelerate cosmic rays to very high energies, little is known about the spectrum of cosmic rays produced by a typical AGN. We have assumed the following form of the spectrum:

$$j(E) \propto E^{-\alpha} \exp(-E/E_{\text{max}}) \exp(-E_{\text{min}}/E). \quad (2)$$

The results do not depend on the lower energy cutoff, but the required source power does. We used $E_{\text{min}} = 10^{13}$ eV, and we explored different values of E_{max} and α . The best fit to the IceCube flux (without overshooting the diffuse cosmic-ray and gamma-ray backgrounds) was obtained for $\alpha = 2.6$, $E_{\text{max}} = 3 \times 10^{17}$ eV. We note that the corresponding gamma factor of a proton at the site of acceleration is close to the maximal value obtained in some detailed simulations [17].

The contribution of distant sources depends on their evolution with redshift. Following the analysis of Ref. [26], we parameterize the source density evolution as

$$\rho(z) = \begin{cases} (1+z)^m, & 0 < z < z_1 \\ (1+z_1)^m, & z_1 < z < z_2 \\ (1+z_1)^m 10^{k(z-z_2)}, & z > z_2 \end{cases} \quad (3)$$

Here m, z_1, z_2 , and k are parameters obtained from fitting the observational data; they take different values for different AGN X-ray luminosities L_x . Hasinger *et al.* [26] obtain the following parameters based on observational data:

$L_x, \text{erg/s}$	$10^{42.5}$	$10^{43.5}$	$10^{44.5}$	$10^{45.5}$
m	4.0 ± 0.7	3.4 ± 0.5	5.0 ± 0.2	7.1 ± 1.0
z_1	0.7	1.2	1.7	1.7
z_2	0.7	1.2	2.7	2.7
k	-0.32	-0.32	-0.43	-0.43
$W_p, 10^{40} \frac{\text{erg}}{\text{s Mpc}^3}$	7.0	6.0	1.3	0.22

TABLE I. Evolution parameters for AGN with different values of the X-ray power L_x inferred from observational data [26] are shown in the upper part of the table. The required power per unit volume W_p of cosmic rays with energies $E_p > 10^{13}$ eV was calculated under the assumption that an average AGN is described by one of these evolution models.

We will consider all of these types of redshift evolution because one does not know whether the X-ray luminosity is well correlated with the power of cosmic ray emission.

For each neutrino flavor we calculate the expected number of events in the energy interval of interest by convolving their predicted spectrum with the experimental exposure given in Ref. [1]. The overall flux normalization is chosen on the basis of the following criteria: (i) the predicted average total number of neutrino events \bar{N}_ν in the energy range $0.4 \text{ PeV} < E < 6 \text{ PeV}$ must be as close as possible to the observed value $N_\nu = 2$ (68% CL interval around 2 is shown in Fig. 1); (ii) the Poisson probability to observe at least 1 event above 6 PeV in the model must be less than 0.68, that is $\bar{N}_\nu^{up} < 1.14$; (iii) diffuse photon flux should not exceed the Fermi upper bound; (iv) the predicted cosmic ray flux should not exceed the observed flux, for which we use the KASCADE-Grande results [27].

The results of our numerical calculations are shown in Fig. 1. As one can see from the figure, neutrinos produced in interactions of cosmic rays with background photons can account for the observed neutrino flux reported by IceCube collaboration in the case of strong evolution and high EBL of Ref. [22].

The energy requirements per source are consistent with what is expected from AGN. For each of the models shown in Table I and in Fig. 1, we calculated the emissivity at $z = 0$ in cosmic rays with energies above $E_{\text{min}} = 10^{13}$ eV. The results vary from 2×10^{39} erg/s/Mpc³ to 7×10^{40} erg/s/Mpc³. Assuming the AGN density of $10^{-5}/\text{Mpc}^3$ [29], one obtains an individual AGN luminosity of $L_0 \simeq 10^{44}$ erg/s for the lower end of the above range. This is a reasonable luminosity, which corresponds to the Eddington mass of $10^6 M_\odot$. (AGN jets can exceed the Eddington limit, but, in our case, the average

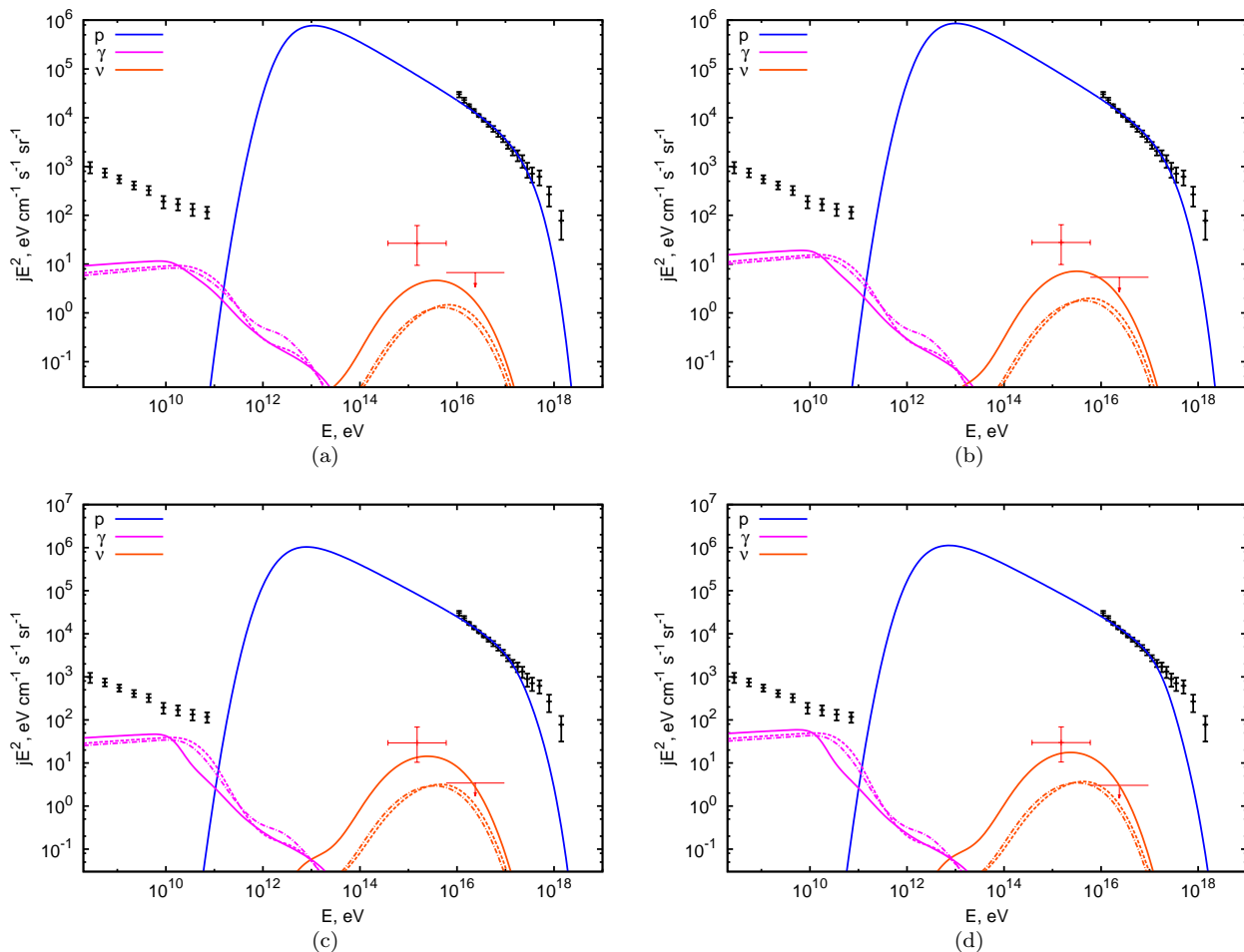


FIG. 1. Predicted spectra of PeV neutrinos (red lines) compared with the flux measured by the IceCube experiment [1]. The IceCube data points (red) are model-dependent 68% confidence level flux estimates obtained by convolving the IceCube exposure with the predicted neutrino spectrum. The predicted spectra are shown for the sum of three flavors; each flavor contributes, roughly, 1/3. The solid, dashed, and dash-dotted red lines correspond to the EBL models of Refs. [22], [23], and [25], respectively. The evolution parameters for each plot are listed in table I for (a) $L_x = 10^{42.5}$ erg/s, (b) $L_x = 10^{43.5}$ erg/s, (c) $L_x = 10^{44.5}$ erg/s, (d) $L_x = 10^{45.5}$ erg/s. In all cases, we assumed the proton spectral index $\alpha = 2.6$ and the maximal proton energy $E_{\text{max}} = 3 \times 10^{17}$ eV. Also shown are the predicted gamma ray (lower curves below 10 TeV) and cosmic ray (upper curve) fluxes. The cosmic ray data points above 10 PeV are based on KASCADE-Grande [27]; the diffuse gamma-ray background data points below 1 TeV are due to Fermi [28].

AGN is expected to operate well below the Eddington luminosity.) This is also consistent with the analyses of Refs. [6, 9].

Future results from IceCube may help constrain models of cosmic ray acceleration in AGN. We note that cosmic ray flux provides a stronger constraint than the diffuse gamma-ray background. Composition measurements based on the data of KASCADE-Grande [27] are subject to large uncertainties in the Monte Carlo simulations, especially in the energy range of interest to us. Furthermore, local galactic magnetic fields can affect the flux and composition of cosmic rays with energies below 10^{17} eV (and even those with higher energies [30]), making it difficult to connect the locally measured composition to that of extragalactic sources. Therefore, we

used the total cosmic ray flux as the upper bound.

In summary, we have examined the recent observations of the IceCube experiment in light of the model that explains the spectra of distant blazars by secondary gamma rays produced in cosmic-ray interactions along the line of sight [4–12]. The same interactions result in a neutrino spectrum peaked at 1 PeV [4]. We have shown that distant AGNs can generate a spectrum of neutrinos with a peak at 1 PeV and with a flux that is consistent with the IceCube results.

The authors thank J. Beacom, F. Halzen, and D. Hooper for helpful, stimulating discussions. A.K. was supported by DOE Grant DE-FG03-91ER40662 and by the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan. O.K. was sup-

ported by the grant of the Russian Ministry of Education and Science No. 8412 and grant of the President of the Russian Federation NS-5590.2012.2.

-
- [1] A. Ishihara, talk at the *Neutrino 2012* conference, June, 2012, Kyoto, Japan; F. Halzen, talk at *Neutrino Oscillations Workshop (NOW- 2012)*, September 9–16, 2012, Otranto, Lecce, Italy.
- [2] A. Bhattacharya, R. Gandhi, W. Rodejohann and A. Watanabe, JCAP **1110** (2011) 017 [arXiv:1108.3163 [astro-ph.HE]].
- [3] I. Cholis and D. Hooper, arXiv:1211.1974 [astro-ph.HE]; R. -Y. Liu and X. -Y. Wang, arXiv:1212.1260 [astro-ph.HE]. M. D. Kistler, T. Stanev and H. Yuksel, arXiv:1301.1703 [astro-ph.HE].
- [4] W. Essey, O. E. Kalashev, A. Kusenko and J. F. Beacom, Phys. Rev. Lett. **104** (2010) 141102 [arXiv:0912.3976 [astro-ph.HE]].
- [5] W. Essey and A. Kusenko, Astropart. Phys. **33**, 81 (2010).
- [6] W. Essey, O. Kalashev, A. Kusenko and J. F. Beacom, Astrophys. J. **731**, 51 (2011).
- [7] W. Essey and A. Kusenko, Astrophys. J. **751**, L11 (2012).
- [8] K. Murase, C. D. Dermer, H. Takami and G. Migliori, Astrophys. J. **749**, 63 (2012).
- [9] S. Razzaque, C. D. Dermer and J. D. Finke, Astrophys. J. **745**, 196 (2012).
- [10] A. Prosekin, W. Essey, A. Kusenko and F. Aharonian, Astrophys. J. **757**, 183 (2012).
- [11] F. Aharonian, W. Essey, A. Kusenko and A. Prosekin, arXiv:1206.6715 [astro-ph.HE].
- [12] Y. G. Zheng, T. Kang, Astrophys. J. **764**, 113 (2013).
- [13] F. W. Stecker, M. G. Baring and E. J. Summerlin, Astrophys. J. **667**, L29 (2007) [arXiv:0707.4676 [astro-ph]].
- [14] E. Lefa, F. M. Rieger and F. Aharonian, Astrophys. J. **740**, 64 (2011) [arXiv:1106.4201 [astro-ph.HE]].
- [15] C. Dermer and B. Lott, J. Phys. Conf. Ser. **355**, 012010 (2012) [arXiv:1110.3739 [astro-ph.HE]].
- [16] A. De Angelis, O. Mansutti and M. Roncadelli, Phys. Rev. D **76**, 121301 (2007); M. Simet, D. Hooper and P. D. Serpico, Phys. Rev. D **77**, 063001 (2008); D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. Montanino and M. Roncadelli, Phys. Rev. D **86**, 075024 (2012); M. Meyer, D. Horns and M. Raue, arXiv:1211.6405 [astro-ph.HE].
- [17] L. Sironi, A. Spitkovsky and J. Arons, arXiv:1301.5333 [astro-ph.HE].
- [18] W. Essey, S. Ando and A. Kusenko, Astropart. Phys. **35**, 135 (2011) [arXiv:1012.5313 [astro-ph.HE]].
- [19] E. Roulet, G. Sigl, A. van Vliet and S. Mollerach, arXiv:1209.4033 [astro-ph.HE].
- [20] M. D. Kistler, T. Stanev and H. Yuksel, arXiv:1301.1703 [astro-ph.HE].
- [21] G. B. Gelmini, O. Kalashev and D. V. Semikoz, JCAP **1201**, 044 (2012) [arXiv:1107.1672 [astro-ph.CO]].
- [22] F. W. Stecker, M. A. Malkan and S. T. Scully, Astrophys. J. **648**, 774 (2006).
- [23] T. M. Kneiske et al., Astron. Astrophys. **386**(2002) 1; *ibid.*, **413** (2004) 807.
- [24] J. R. Primack, R. C. Gilmore and R. S. Somerville, AIP Conf. Proc. **1085**, 71 (2009); A. Franceschini, G. Rodighiero and M. Vaccari, Astron. Astrophys. **487**, 837 (2008); [arXiv:0805.1841 [astro-ph]]. J. D. Finke, S. Razzaque and C. D. Dermer, Astrophys. J. **712**, 238 (2010); F. W. Stecker, M. A. Malkan and S. T. Scully, Astrophys. J. **761**, 128 (2012).
- [25] Y. Inoue, S. Inoue, M. A. R. Kobayashi, R. Makiya, Y. Niino and T. Totani, arXiv:1212.1683 [astro-ph.CO].
- [26] G. Hasinger, T. Miyaji and M. Schmidt, Astron. Astrophys. **441**, 417 (2005) [astro-ph/0506118].
- [27] W. D. Apel et al. [Grande Collaboration], Astropart. Phys., in press [arXiv:1206.3834 [astro-ph.HE]].
- [28] A. A. Abdo et al. [Fermi-LAT Collaboration], Phys. Rev. Lett. **104**, 101101 (2010) [arXiv:1002.3603 [astro-ph.HE]].
- [29] E. Treister, C. M. Urry and S. Virani, Astrophys. J. **696**, 110 (2009) [arXiv:0902.0608 [astro-ph.CO]].
- [30] A. Calvez, A. Kusenko and S. Nagataki, Phys. Rev. Lett. **105**, 091101 (2010) [arXiv:1004.2535 [astro-ph.HE]].